Atomic Energy Control Board
P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
K1P 5S9

INFO-0283

ASSESSMENT OF THE SIGNIFICANCE OF ORGANICALLY-BOUND TRITIUM IN ENVIRONMENTAL MATERIALS

by

R.M. Brown
AECL-CRNL

A research report prepared for the
Atomic Energy Control Board
Ottawa, Canada

September 1988

Canada

Research report

ASSESSMENT OF THE SIGNIFICANCE OF ORGANICALLY-BOUND TRITIUM IN ENVIRONMENTAL MATERIALS

ABSTRACT

The present state of knowledge of the significance, with respect to dose, of organically-bound tritium (OBT) in diet items has been reviewed. Ratios of the specific activity of the OBT to that of the free water (HTO) in foodstuffs have been commonly reported in the range of 1 to 4. A metabolism model of Etnier, Travis and Hetrick that takes direct assimilation of food OBT into account indicates that such levels result in a dose two to three times greater than that calculated solely on the basis of body water tritium content. Very high OBT/HTO values reported by Italian studies on food items are discounted. It is recommendend that OBT/HTO measurements be done on Canadian diet items and that tritium metabolism models be more thoroughly evaluated.

RÉSUMÉ

Le présent rapport examine l'état des connaissances actuelles, du point de vue des doses, sur le tritium lié aux molécules organiques des aliments. On rapporte ordinairement que le ratio entre l'activité spécifique du tritium lié aux molécules organiques et de l'eau tritiée à l'état libre dans les aliments se situe aux environs de 1:4. Un modèle de métabolisme d'Etnier, Travis et Hetrick qui tient compte de l'assimilation directe du tritium lié aux molécules organiques dans les aliments, indique qu'un tel niveau entraîne des doses deux à trois fois supérieures à celles qui sont calculées uniquement à partir de la teneur en tritium dans les liquides organiques. Les ratios très élevés de tritium lié aux molécules organiques par rapport à l'eau tritiée qui ont été rapportés dans les études italiennes n'ont pas été retenus. Il est recommandé de mesurer les aliments canadiens pour déterminer le ratio du tritium lié aux molécules organiques par rapport à l'eau tritiée à l'état libre dans les aliments et d'évaluer plus en profondeur les modèles de métabolisme du tritium.

DISCLAIMER

The Atomic Energy Control Board is not responsible for the accuracy of the statements made or opinions expressed in this publication and neither the Board nor the author assume liability with respect to any damage or loss incurred as a result of the use made of the information contained in this publication.

ASSESSMENT OF THE SIGNIFICANCE OF ORGANICALLY-BOUND TRITIUM IN ENVIRONMENTAL MATERIALS

SUMMARY

Reports of elevated levels of organically-bound tritium relative to aqueous tritium in foodstuffs and human tissue have raised concern about the effect of such conditions on the validity of dose estimates based on the assumption that all tritium intake is rapidly dispersed throughout the body water and may be monitored adequately by urinalysis. Exposure chamber and feeding studies have demonstrated that a portion of the organically-bound tritium (OBT)in diet items is assimilated quickly without oxidation and distribution in the body water. A transfer model incorporating a fast direct assimilation route for OBT in food indicates that dose estimated taking into account such assimilation will be significantly higher than that based simply on the HTO content of food and drink if the OBT/HTO ratio of the food is in the range 2 to 4, as has been observed commonly. Values much higher than this reported for diet items in Italy are discounted in view of the limitations of the sensitivity of the techniques used and lack of correlation with data from other laboratories. However, there are few other measurements of OBT/HTO in meats, the item that is particularly high in the Italian results. It seems advisable that some measurements of OBT/HTO be done on Canadian diet items to assess the situation here.

It must be pointed out that there should be no concern about underestimating the occupational dose of CANDU nuclear power station workers by limiting analyses to urine. Such occupational exposure is predominately to HTO and does not involve OBT which might by-pass the body water and be missed by urinalysis. Contact of bare skin with HT contaminated surfaces results in formation of OBT in the subject with the dose to skin at the point of contact being limiting. Doses from the OBT formed to other tissues are several orders of magnitude smaller. In any case where tritiated organic compounds are involved, examination of subjects for elevated OBT, e.g. in blood components, would be advisable.

In brief, OBT/HTO ratios greater than one have been commonly observed in foodstuffs and could result in a dose up to 3 times higher than that calculated solely on the basis of the HTO content of the food. Since normal concentrations of OBT in environmental materials are insignificant, this would only be of concern in the case of prolonged contamination of the general environment where foodstuffs are grown. However, in view of reports of very high OBT/HTO in meat, even though uncorroborated, it would seem advisable to have some reliable analyses done on Canadian diet items, particularly meats. There is no concern that monitoring of occupational exposure in CANDU power stations by urinalysis is inadequate.

TABLE OF CONTENTS

		Page No.
Abstract		
Summary		
1.0	Forms of Tritium in Organic Matter	1
2.0	Significance of OBT in the Diet	2
3.0	OBT/HTO Ratios in Environmental Materials	2
	3.1 Measurement	2
	3.2 Data	3
4.0	Exposure Experiments	4
	4.1 HTO Exposure	4
	4.2 OBT Feeding	5
	4.3 HTO and OBT Feeding	5
	4.4 HT Exposure	6
5.0	Conclusions	6
6.0	Recommendations	7
7.0	References in the Text	8
8.0	Relevant Literature Not Cited in the Text	11
9.0	Subject Index for References	14
10.	Tables	15
11.	Figures	24

ASSESSMENT OF THE SIGNIFICANCE OF ORGANICALLY-BOUND TRITIUM IN ENVIRONMENTAL MATERIALS

R.M. Brown
Environmental Research Branch
Chalk River Nuclear Laboratories
Atomic Energy of Canada Limited

1.0 Forms of Tritium in Organic Matter

Tritium occurs in organic matter in three forms:

i) In the free water associated with the matter.
ii) Bound to oxygen, sulphur and nitrogen atoms in compounds of the material. This tritium is exchangeable with water in the system to varying degrees depending on molecular structures.

iii) Bound to carbon atoms in the material. This tritium is non-exchangeable and only released on decomposition of the organic compound.

The exchangeable tritium in (ii) will be in equilibrium with the aqueous component of the system and so, from the point of view of specific activity, may be considered as part of the overall aqueous complement of the system. The free water tritium and the exchangeable tritium may have a different specific activity than the local environmental waters if the material has originated in a different region but will tend to equilibrate with local atmospheric moisture.

Component (iii) is designated Organically Bound Tritium (OBT). The OBT/HTO ratio of a material refers to the ratio of the specific activity (Bq/g hydrogen) of the carbon-bound hydrogen to that of the free water of the material. For ease of analysis exchangeable tritium is often measured along with carbon-bound tritium by simple removal of the free water (drying) and combustion in preparation for activity measurement. Carbon-bound tritium can be measured separately by equilibrating the material with tritium-free water prior to combustion. Carbon-bound tritium is sometimes designated Non-Exchangeable Tritium (NET) to differentiate it from combined exchangeable and carbon-bound tritium.

At the time of its formation, OBT has essentially the same specific activity as the water from which it was formed (OBT/HTO ratio = 1.0) since net isotopic fractionation in the biochemical reactions involved is slight.

2.0 Significance of OBT in the Diet

At present dose to the human body from intake of tritium is based on the assumption that all intake is in the form of water or is rapidly oxidized to water in the gut and is distributed uniformly throughout the body water (1,2). Bennett (3) has represented this by a three compartment transfer model, Figure 1, which consists of a body water reservoir, $t_{1/2}$ = 10 days, and two dependent organic hydrogen reservoirs, $t_{1/2}$ = 30 d and 450 d, corresponding to observed discharge rates from exposed individuals. Reports of elevated levels of organically-bound tritium (OBT) relative to aqueous tritium in plants and animals and evidence that the OBT content of animals fed tritiated food respond rapidly have raised concern that dose is underestimated in considering only intake to the body water compartment. Etnier, Travis and Hetrick (4) proposed a four compartment transfer model, Figure 2, to include a pathway for rapid assimilation of a portion of the OBT intake without oxidation. They argue that such a pathway is in line with known rapid assimilation of some lipid materials by the body. Furthermore, it has long been recognized that some amino acids are not synthesized in the body and must be acquired intact from the diet. Myers and Johnson (5) have reviewed the metabolism of organically bound tritium.

If OBT is assimilated directly it will not be evidenced in the body water. If the specific activity of intake OBT is the same as that of intake HTO, the dose estimate for chronic intakes will not be affected if the measured specific activity of body water is applied to the complete complement of H in the body and account is taken of the long residence time of OBT in the body. The Bennett model indicates a cumulative dose after 2000 d of 1.2 times that estimated from the free body water compartment alone. The four compartment model of Etnier et al yields a cumulative dose after 2000 d of 1.74 times the dose contributed by the free body water compartment alone. If the specific activity of intake OBT is greater than that of intake water, the dose estimate based on body water will be further underestimated. Figure 3 shows the dependence of dose estimate (cumulative after 2000 d) on the mean OBT/HTO ratio of the food items of the diet as indicated by the ET&H model. At a mean OBT/HTO ratio of 2 for the food items of the diet, dose estimate is 2.1 times that contributed by the free body water alone. It is evident that the OBT/HTO ratio of the diet should be taken into account in dose considerations.

3.0 OBT/HTO ratios in Environmental Materials

3.1 Measurement

Great care must be taken in the measurement of OBT at environmental levels. McFarlane (6) has pointed out the opportunities for cross-contamination of samples and contamination by exchange with the laboratory atmosphere. Most measurements have been done in laboratories at nuclear research centres where atmospheric HTO levels are usually elevated above the normal environmental levels one is trying to measure. For proper analysis the following points have to be achieved:

a) A sample of at least 5 g is required to get enough counts for acceptable statistical accuracy. Commercial combustion units can accommodate a maximum of 1 g.

b) Complete removal of free water from the material. The free water may have been contaminated by exposure to the lab atmosphere after sampling.

c) Removal of exchangeable tritium from the material. This is accomplished by repeated soakings in T-free water or exchange with T-free steam.

d) Final drying in the combustion system. This cannot be accomplished satisfactorily in a commercial combustion unit. The dried material is very hygroscopic and will pick up water from the lab air if exposed in transferring from a drying system to a combustion system. Table I illustrates contamination on drying samples in an air oven.

e) Protection of all samples against exposure to the lab atmosphere before and after drying and combustion.

f) Long counting time in a low background system.

Usually combustion in a quartz tube with a flow of dry O_2 is used to handle large enough samples. Strack (7) uses a plasma combustion system. A 2 litre Parr combustion bomb is used at Chalk River. It will handle up to 10 g fresh weight of material. In all cases drying in the combustion system is slow but necessary.

3.2 Data

Our first experience of OBT/HTO > 1.0 in plants growing under steady state conditions was with tomatoes and cucumbers grown in an experimental greenhouse near the Pickering Nuclear Generating Station (8). We observed OBT/HTO in the range 2.6 to 4.8 (Table II) in 18 samples. Since that time we have analyzed many samples of grass, leaves and pine needles around the CRNL site and found values from 0.6 to 4., but generally in the range 1 to 2. I believe the explanation in these cases is the following. Tritium in this area is dispersed as atmospheric HTO vapour and leaf moisture in equilibrium with this atmospheric vapour has a higher tritium content than the soil moisture which constitutes the main water body in the plant. Photosynthesis in the leaves produces organic matter having a higher tritium content than that in the main water component of the plant.

Table III presents data reported by Bogen et al (9) for New York soils, foods and human tissues. During the 1960's and 1970's when these samples were taken, there were wide fluctuations in the levels of HTO and HT in the environment as a result of thermonuclear bomb tests. It is easy to see how these fluctuations could put OBT/HTO in plants and animals out of equilibrium since the organic pool of H responds much more slowly than the aqueous pool for both intake and discharge. In Bogen's results, the high

values for soil must result from the persistence of OBT formed during the preceding decade when environmental levels were generally high. Workers in France (10), Germany (11) and Japan (12) have reported OBT/HTO ratios in the range of 1 to 4. Tables IV, V and Figure 4 present some of the data from the Karlsruhe Nuclear Research Centre. The values are variable, but consistently greater than 1.0. The Karlsruhe data for food items are particularly relevant as are those for Japan (Table VI).

Much higher values have been reported by Belloni and co-workers (13,14,15,16) for Italian food items (Table VII) and human tissues. The higher values for meat than for vegetation is inconsistent with experience on feeding OBT to animals, as discussed in the following section. Additionally they measured much higher concentrations of tritium in human blood than in urine (Table VIII) which in turn was higher than the local environmental HTO levels. They suggest that these levels result from high levels of OBT in the body and that the urine is not an adequate sample of the mean body tritium burden. They do not observe this high ratio of blood to urine tritium in the case of occupational exposure where the augmented exposure was not to OBT. Irlweck & Teherani (17) also measured high blood urine ratios but other workers (18) have not even at environmental levels (19). Consideration of the details of analysis of the Italian and Austrian workers raises doubts about the validity of their data. OBT was measured using a commercial combustion unit limited by sample size and cross-contamination opportunities. The difference in background reported for combustion samples and distilled urine sample is of the same size as the discrepancy between blood and urine counts. It is not evident why the counting background should differ for the two samples. The values they report for precipitation deviate significantly from data of the low level tritium laboratory of the IAEA (20,21) during the period this work was being done (Figure 5) suggesting a contamination problem in their laboratory or local environment.

In summary, it has been common experience to find OBT/HTO ratios > 1.0 in vegetation and food items. Generally these have been around 2. Much higher values obtained in two laboratories are discounted on the basis of their analytical technique.

4.0 Exposure Experiments

Numerous studies have been done on the incorporation of tritium into aquatic and terrestrial plants and animals. Many of these are included in the Bibliography and results have been compiled in Symposia Proceedings and Review Articles. A few will be discussed here to see if the phenomena observed may explain non-equilibrium OBT/HTO in plants and animals.

4.1 HTO Exposure

Plants, trees, cows, pigs, mice, rabbits, fish, algae and man have all been studied.

The Tissue Free Water Tritium (TFWT) in plants, animals and fish quickly responds to HTO exposure, the rate depending on the size of the body water compartment of the specimen. The TFWT level usually rises to 60 - 80% of the tritium concentration of the exposure water, never exceeds it. In many experiments not all routes of water intake were tritiated, e.g. irrigation water but not atmospheric moisture, drinking water but not water contained in food or the atmosphere. The extent of approach to the concentration of exposure water was correspondingly affected. Aquatic plants and animals come closer to equilibrium than terrestrial plants and animals probably because of more complete tritiation of all intake routes.

Organic-bound tritium responds much more slowly to HTO exposure and seldom exceeds 20% of the concentration of the exposure water, often being only a few percent. Long-term approach to equilibrium is limited by remains of original tritium-free organic constituents in the specimen. On cessation of exposure, decrease of OBT is similarly slow, the OBT being decomposed and discharged as HTO.

Spencer (22) studied the varying uptake of tritium by the fruit, new foliage and old foliage of tomato plants exposed to HTO. Figure 6 shows the effect of exposure to atmospheric HTO on the OBT/HTO ratio of the different components. Old foliage takes up TFWT readily but synthesizes little OBT, so the OBT/HTO ratio is slow to rise. New foliage takes up TFWT quickly and also synthesizes OBT quickly, OBT/HTO approaches 1. However, with time OBT formation drops off and the OBT/HTO ratio falls. The green fruit has little exchange with atmospheric moisture, hence maintains a low TFWT. However, the fruit incorporates photosynthetic products translocated from the foliage, so the OBT exceeds the TFWT. With time more tritiated water comes into the fruit from the rest of the plant and the OBT/HTO ratio falls below 1.

4.2 OBT Feeding

Fish, cows, pigs, mice, rats, rabbits have all been studied. The TFWT responds much more slowly and to much less extent than in the case of HTO administration. The TFWT remains lower than the OBT. On cessation of feeding, the TFWT decreases in parallel with the OBT.

The OBT of the specimen responds quickly and reaches higher levels than the TFWT, so OBT/HTO > 1.0 occurs. The experience is similar with various animals and even fish. The OBT never exceeds the concentration of administered OBT. Hence, it does not seem that the OBT/HTO of meat could ever exceed that in feed.

4.3 HTO and OBT Feeding

Figure 7 contrasts the effect of feeding a lactating cow tritiated water and tritiated fodder (23,24). Tritium appears in both the aqueous and the organic components of the milk in both cases, but with HTO administration the aqueous components show more rapid and much greater response than do the organic components. On the other hand, with tritiated

fodder, the organic components show the strong response and the aqueous components a weaker response. Here, an OBT/HTO > 1. is demonstrated in an animal product.

Rodgers (25) fed mice independently tritiated water, tritiated amino acids and both. His results on the rate of uptake and the rate of excretion after cessation of exposure are shown in Table IX. The steady-state specific activity of the TFWT was greater for HTO feed than diet feed and together they equalled that observed for simultaneous feeding of HTO and T-diet. Only a single reservoir was evident on uptake or elimination. The steady-state specific activity of the OBT was greater for diet feed than HTO feed. In fact, it appears to exceed the specific activity of the diet, but is less when the two are expressed per gram of protein, the tritium having been fed as tritiated amino acid. On elimination two reservoirs were evident, the first having a turnover rate 1/2 of that of incorporation and the second a turnover rate 1/10 that of incorporation. The rate of formation of HTO from T-diet feed was about the same as the rate of formation of OBT from HTO feed.

Moghissi, Bretthauer and Petzer (26) fed mice HTO and tritiated food of the same specific activity through three generations. Table X presents their results on the OBT/HTO ratio of various organs of all generations. They found no statistically significant deviation from a value of 1.0.

4.4 HT Exposure

In some HT exposure studies, trace amounts of OBT were observed in pine needles (27), corn, tomato and poplar foliage (28) but the levels were so low as to be attributable to oxidation and uptake via the soil. In recent field experiments (29,30) no evidence for OBT formation directly from HT has been found.

Contact of bare skin with HT contaminated surfaces results in formation of OBT in the subject (18,31,32) with the dose to skin at the point of contact being limiting. Doses from the OBT formed to other tissues are several orders of magnitude smaller.

5.0 Conclusions

i) It has been definitely demonstrated that OBT is directly assimilated to a limited extent in feeding experiments.

ii) A proper transfer model for dose estimate should allow for this .

iii) When OBT/HTO is > 1.0, dose will be underestimated if based solely on body water content.

iv) Measurements by a number of workers indicate that OBT/HTO of food items is generally > 1.0 but that it is unlikely that the mean OBT/HTO of diet will exceed 2.

v) An OBT/HTO of 2.0 for the organic portion of food items results in a dose 2.1 times that contributed by the free body water alone according to the Etnier, Travis Hetrick transfer model.

vi) Meat should never have OBT/HTO greater than that of the feed, according to results from experimental feeding.

vii) The effect of OBT/HTO > 1.0 in environmental materials is important only in the case of long-term contamination of the area where foods and forage crops are grown. The immediate vicinity of a nuclear power station might be such a case.

viii) Urinalysis is a valid monitoring technique for occupational exposure where no OBT is involved, such as in nuclear power stations.

6.0 Recommendations

It must be accepted that direct assimilation of OBT occurs and has an effect on dose. In any case where tritiated organic compounds are involved, examination of subjects for elevated OBT, e.g. in blood components, in hair, (33) would be advisable. In the case of exposed dial painters, no difference has been observed between blood and urine tritium levels.

The Etnier, Travis and Hetrick model, which gives the above estimates for the augmentation of dose due to elevated OBT/HTO ratios in food items, should be more thoroughly evaluated. It is more realistic than the NCRP model in representing recognized processes involved in the transfer of tritium from food to body tissue. However, it was "validated" by reference to the questionable data for Italian diet and tissue items (34). It should be validated against more reliable OBT/HTO data before it is accepted as taking proper account of the contribution of OBT to total dose.

Proper application of any "augmentation" factor to account for additional dose resulting from high OBT/HTO ratios requires knowledge of the OBT/HTO ratio of diet items. In view of the lack of data on the OBT/HTO ratio of Canadian foods, it would be worthwhile to have some reliable analyses done, perhaps on a site specific basis, to gain assurance that some unknown factor that may cause unusually high values such as reported for Italy is not present.

REFERENCES (in text)

1. ICRP,1959. Recommendations of the International Commission on Radiological Protection, Publication 2. International Commission on Radiological Protection, Pergamon Press, New York.

2. National Council on Radiation Protection and Measurement (NCRP). 1979 "Tritium in the Environment." NCRP Report No. 62. Washington D.C.

3. Bennett B.G. 1973. "Environmental Tritium and the Dose to Man." Proceedings Third International Congress of the IRPA, Washington, D.C. pp 1047-1053 USAEC Tech. Inf. Center, Oak Ridge, TN.

4. Etnier E.L., C.C. Travis, D.M. Hetrick. 1984. "Metabolism of Organically Bound Tritium in Man." Radiation Research 100 pp 487-502.

5. Myers D.K., J.R. Johnson. 1987. "Toxicity and Dosimetry of Tritium. A Review." Report prepared for the Advisory Committee on Radiological Protection, Atomic Energy Control Board, Ottawa, Ontario.

6. McFarlane J.C. 1976. "Tritium Fractionation in Plants." Environ. Exp. Bot. Vol. 16, pp 9-14.

7. Strack S., L.A. Koenig. 1981. "Determination of Organically Bound Tritium in Environmental Samples by Application of the Oxidizing Plasma Technique." Kernforschungszentrum Karlsruhe Report KfK 3249.

8. Gorman D.J. 1980. "Levels of Tritium and Carbon-14 in Greenhouse Produce at Pickering NGS." Ontario Hydro Report SSD-80-2.

9. Bogen D.C., G.A. Welford, C.G. White. 1979. "Tritium Distribution in Man and his Environment." Proceedings IAEA Symposium on Behaviour of Tritium in the Environment. STI/PUB/498 pp 567-574.

10. Belot Y., C. Caput, D. Gauthier. 1986. "Distribution of the Organically Bound Tritium in Vegetation Exposed to Fallout." Radiat. Prot. Dosim. 16 pp 111-113.

11. Koenig L.A., S. Fark, S. Hempelmann, K.-G. Langguth,G. Pagliosa, D. Papadopoulos, S. Strack. 1987. "Untersuchungen zum Transport von Tritium in der Umwelt." Kernforschungszentrum Karlsruhe Report KfK 4131.

12. Hisamatsu S.,Y. Takizawa, T. Abe, T. Katsumata 1986. "Determination of Fallout Tritium in Food." Report of the Energy Project (Nuclear Fusion) of Ministry of Education and Culture of Japan. No. 60050024.

13. Belloni P., G. Cave Bondi, G.F. Clemente, S. Di Pietro, S. Merli, G. Santori, C. Sgarbazzini. 1982. "Tritium and Plutonium Content in Human Tissues of the General Population in Italy." Proceedings of the Third Int. Symp. on Radiological Protection Advances in Theory and Practice, Inverness, Scotland, Vol.2, pp 518-524.

14. Ingrao G., P. Belloni, G.F. Clemente, S. Di Pietro, G. Santori. 1983. "Tritium and Plutonium content in the Food- Chain in Italy." Proceedings of a Seminar on The Transfer of Radioactive Materials in the Terrestrial Environment Subsequent to an Accidental Release to the Atmosphere. Dublin, Vol II, pp 481-495.

15. Belloni P., G.F. Clemente, S. Di Pietro, G. Ingrao. 1983. "Tritium Levels in Blood and Urine Samples of the Members of the Italian General Population and Some Exposed Subjects." Radiation Protection Dosimetry, Vol. 4, No. 2 pp 109-113.

16. Belloni P., G.F. Clemente, S. Di Pietro, G. Ingrao, F. Breuer. 1984. "Tritium Metabolism in the Human Body." Proceedings of a Seminar on the Environmental Transfer to Man of Radionuclides Released from Nuclear Installations. Brussels, pp 677-676.

17. Irlweck K., D.K. Teherani. 1976. "Tritium Concentration in Urine and Blood of Austrian Residents." Health Physics Vol. 30, pp 407-409.

18. Johnson J.R., R.M. Brown, D.K. Myers. 1986. " An Overview of Research at CRNL on the Environmental Aspects, Toxicity, Metabolism and Dosimetry of Tritium." Radiation Protection Dosimetry Vol. 16 No. 1-2, pp 17-21.

19. Mattern F.C.M., L. Strackee. 1975. "Tritium in Human Blood and Urine Due to Environmental Uptake." Third European Congress of the IRPA, Amsterdam.

20. International Atomic Energy Agency. 1983. "Environmental Isotope Data No.7: World Survey of Isotope Concentration in Precipitation (1976-1979)." Tech. Reports Series No. 226.

21. International Atomic Energy Agency. 1986. "Environmental Isotope Data No.7: World Survey of Isotope Concentration in Precipitation (1980-1983)." Tech. Reports Series No. 264.

22. Spencer F.S. 1984."Tritiated Water Uptake Kinetics in Tissue Free Water and Organically Bound Fractions of Tomato Plants." Ontario Hydro Research Division Report 84-69-K.

23. Potter G.D., G.M. Vattuone, D.R. McIntyre. 1971. "Metabolism of Tritiated Water in the Dairy Cow." Health Physics Vol. 22 pp 405.

24. International Atomic Energy Agency. 1981. "Tritium in Some Typical Ecosystems." Tech. Reports Series No. 207 p 64.

25. Rodgers D.W., 1988. "Tritium Dynamics in Mice Exposed to Tritiated Water, Tritiated Diet or Both." Ontario Hydro Research Division Report 88-30-K.

26. Moghissi A.A., E.W. Bretthauer, R.G. Patzer. 1987. "Biological Concentration of ^{3}H." Health Physics Vol. 53 No. 4 pp 385-388.

27. Sweet C.W., C.E. Murphy. 1984. "Tritium Deposition in Pine Trees and Soil from Atmospheric Releases of Molecular Tritium." Envir. Sci. Technol. Vol. 18, pp 358-361.

28. Dunstall T.G., G.L. Ogram, F.S. Spencer. 1985. "Elemental Tritium Deposition and Conversion in the Terrestrial Environment." Fusion Tech. Vol. 8 No. 2 Part 2,pp 2551-2556.

29. Canadian Fusion Fuels Technology Project. 1988. "The Canadian HT Dispersion Experiment at Chalk River - June 1987." CFFTP Report in Preparation.

30. Spencer F.S., G.L. Ogram, R.M. Brown. 1988." Field Studies of HT Behaviour in the Environment: 3. Tritium Deposition and Dynamics in Vegetation." Fusion Technology In press.

31. Eakins J.D., W.P. Hutchinson, A.E. Lally. 1975. "The Radiological Hazard from Tritium Sorbed on Metal Surfaces. " Health Physics Vol. 28, p 213.

32. Johnson J.R., D.W. Dunford. 1985. "Dosimetric Models of ^{3}H from Skin Absorption Following Contact with T_2-Contaminated Surfaces." Health Physics Vol. 48, pp 110-113.

33. Pietrzak-Flis Z., I. Radwan.1984. "Dose Estimation from Chronic Tritium Exposure Using Tritium Concentrations in Urine and Hair." Health Physics Vol.46, No. 2 pp 460-464.

34. Travis C.C., E.L. Etnier, D.M. Hetrick. 1984. "Validation of a Metabolic Model for Tritium." Radiat. Res. Vol. 100,pp 503-509.

Relevant literature not cited in the text.

35. Adams L.W., T.J. Peterle, G.C.White. 1979. "Tritium Behaviour in Aquatic Plants and Animals in a Freshwater Marsh Ecosystem." Proceedings IAEA Symposium on Behaviour of Tritium in the Environment. STI/PUB 498 pp 231-24.

36. Belloni P., G.F. Clemente, S.Di Pietro,G. Ingrao. 1984. "Fallout Tritium Levels in Environmental and Biological Samples in Italy." European Seminar on Risk from Tritium Exposure.

37. Belot Y. 1986. "Tritium in Plants: A Review." Rad. Prot. Dosimetry Vol. 16 No. 1-2, pp 101-105.

38. Blaycock B.G., F.O. Hoffman, M.L. Frank.1986. "Tritium in the Aquatic Environment." Rad. Prot. Dosimetry, Vol. 16, No. 1-2, pp 65-71.

39. Blaylock B.G., M.L. Frank.1979. "Distribution of Tritium in a Chronically Contaminated Lake." Proceedings IAEA Symposium on Behaviour of Tritium in the Environment.STI/PUB 498 pp 247-256.

40. Bovard P., J. Delmas, Y. Belot, H. Camus, A. Grauby, R. Kirchman, J. Van den Hoek. 1979. "Transfert a la Ration Alimentaire du Tritium Emis par les Installations Nucleaires." Proceedings IAEA Symposium on Behaviour of Tritium in the Environment.STI/PUB 498 pp 419-431.

41. Bruner H.D. 1973. "Distribution of Tritium between the Hydrosphere and Invertebrates." In TRITIUM. Publisher: Messenger Graphics, Las Vegas. pp 303-322.

42. Carston A.L. 1979. "Tritium in the Environment." Advances in Radiation Biology Vol. 8, pp 419-457.

43. Cigna A. 1986. "Behaviour of Tritium in Aquatic Systems." Rad. Prot. Dosimetry,Vol. 16,NO. 1-2, pp 73.

44. Clemente G.F., P. Belloni, S. Di Pietro,G. Santori,G.P. Santatoni. 1979. "Tritium and Plutonium Content of the Diet and Transfer to Man." Proceedings of IAEA Symposium on Biological Implications of Radionuclides Released from Nuclear Industries.

45. Cohen L.K., T.J. Kneip. 1973. "Environmental Tritium Studies at a PWR Power Plant." In TRITIUM, Publisher: Messenger Graphics, Las Vegas. pp 623-639.

46. Garland J.A., M. Ameen.1979. "Incorporation of Tritium in Grain Plants. Health Physics Vol. 36 pp 35-38.

47. Guenot J., Y. Belot.1984. "Assimilation of ^{3}H in Photosynthesizing Leaves Exposed to HTO." Health Phys. Vol. 47,pp 849-855.

48. Kirchman R., P. Charles, R. Van Brunwaene, J. Remy, G. Koch, J. Van den Hoek. 1977. "Distribution of Tritium in the Different Organs of Calves and Pigs after Ingestion of Various Tritiated Materials." Current Topics in Rad. Res. Quarterly Vol. 12 pp 291-312.

49. Kirchman R., E. Fagniart. 1982. "Bilan de Recherches Experimentale sur le Transfer de l'Eau Tritiee aux Vegetaux Cultives." Annales de l'Association Belge de Radioprotection Vol. 7(3-4) pp 229-246.

50. Kirchman R., S. Bonotto,S.D. Soman, T.M. Krishnamoorthy, T.S. , A.A. Moghissi. 1979. "Transfer and Incorporation of Tritium in Aquatic Organisms." Proceedings IAEA Symposium on Behaviour of Tritium in the Environment.STI/PUB 498 pp 187-204.

51. Kirchman R., G. Koch, V. Adam, J. Van Den Hoek.1973. "Studies on the Food Chain Contamination by Tritium." In TRITIUM, Publisher: Messenger Graphics, Las Vegas. pp 341-348.

52. Koranda J.J., J.R. Martin. 1973. "The Movement of Tritium in Ecological Systems." In TRITIUM, Publisher: Messenger Graphics, Las Vegas. pp 430-455.

53. Krishnamoorthy T.M., T.S. Iyengar, S.D. Soman, G. Solis de Bravo, J.R. Ortiz Magana, C. Archundia, L.L. Martinez de Alva, R.M. de Nulman, N.B. Juan, A. Yuthamanop.1979. "Behaviour of Tritium in the Plant Domain." Proceedings IAEA Symposium on Behaviour of Tritium in the Environment.STI/PUB 498 pp 385-403.

54. Patrick P.H. 1985. "Tritium Uptake Kinetics in Crayfish." Ontario Hydro Research Division Report No.85-183-K.

55. Pietrzak-Flis Z., I. Radwan, Z. Major, M. Kowalska. 1982. "Tritium Incorporation in Rats Chronically Exposed to Tritiated Water or Tritiated Food." J. Radiation Research Vol.22 pp 434-442.

56. Pietrzak-Flis Z., I. Radwan, L. Indeka. 1978. "Tritium in Rabbits after Ingestion of Freeze-dried Tritiated Food and Tritiated Water." Radiation Res. Vol. 76 pp 420-428.

57. Rochalska M., Z. Szot. 1977. "The Incorporation of Organically-bound Tritium of Food into Some Organs of the Rat." J. Radiation Biology Vol. 31 No. 4 pp 391-395.

58. Rodgers David W. 1984. "Dynamics of Tritium Accumulation in Juvenile Rainbow Trout, Salmo gaudneri, Exposed to Tritiated Water, Tritiated Diet or Both." Ontario Hydro Research Division Report No.84-217-K.26

59. Salonen L., J.K. Miettinen. 1982. "Radioecology of Tritiated Water in Subarctic Soils and Vegetation." In Proceedings Series Environmental Migration of Long-lived Radionuclides.

60. Shaw P.V., S.M. Haywood.1986. "A Dynamic Model to Predict the Transfer of Tritium through the Environment." Rad. Prot. Dosimetry Vol. 16 No. 1-2, pp

61. Siri w.,J. Evers. 1962. "Tritium Exchange in Biological Systems." Iaea Symposium Proceedings on Tritium in the Physical and Biological Sciences, Vol. II pp 71-84.

62. Strack S., G. Kistner, C.C. Emers. 1979. "Incorporation of Tritium into Planktonic Algae in a Continuous Culture under Dynamic Conditions." Proceedings IAEA Symposium on Behaviour of Tritium in the Environment.STI/PUB 498 pp 219-230.

63. Takeda H. 1982. "Comparative Metabolism of Tritium in the Rat after a Single Injection of Some Tritiated Organic Compounds versus Tritiated Water." J. Radiation Research Vol. 23 pp 345-357.

64. Takeda H., A. Kiyohiko, T. Iwakura.1985. "Comparison of Tritium Metabolism in Rat Following Single or Continuous Ingestion of Tritium Labelled Wheat Versus Tritiated water." J. Rad. Res. Vol. 26,pp 131-139.

65. Till J.E., E.L. Etnier, H.R. Meyer.1981. "Methodologies for Calculating the Radiation Dose to Man from Environmental Releases of Tritium." Nuclear Safety Vol. 22 No.2 pp 205-213.

66. Van Bruwaene R., et al. 1984. "Transfer of Tritiated Water and Organically-bound Tritium in Pigs and Mice during Pregnancy." Int. J. Rad. Biology Vol. 46 pp 796-.

67. Van Bruwaene R., G.B. Gerber,R. Kirchman, Ivan den Hoek, J. Vankerkom. 1982. "Tritium Metabolism in Young Pigs after Exposure of the Mothers to Tritium Oxide during Pregnancy. Radiation Res. Vol. 91 No. 1 pp 124-134.

68. Van Hees M., R. Kirchman, G.B.Gerber, J. Vankerkom, R. Van Bruwaene. 1986. "Retention in Young Pigs of Organically Bound Tritium Given During Pregnacy and Lactation." Rad. Prot. Dosimetry Vol. 16, No.1-2, pp

69. Van den Hoek J., H.J. ten Have. 1983. "The Metabolism of Tritium and Water in the Lactating Cow." Health Physics Vol. 44 No. 2 pp 127-133.

70. Van den Hoek J., M.H.J. Ten Have, G.B. Gerber, R. Kirchman. 1985. "The Transfer of Tritium- Labelled Organic Material from Grass into Cow's Milk." J. Rad. Res. Vol. 103,pp 105-113.

71. Van den Hoek J., R. Kirchman, N.B. Juan. 1979. "Transfer and Incorporation of Tritium in Mammals." Proceedings IAEA Symposium on Behaviour of Tritium in the Environment. STI/PUB 498 pp 433-444.

Subject Index for References

Reviews: Ref. Nos. 5,24,37,42,48,51,61.

Tritium in Man: Ref. Nos. 2,3,5,13,15,17,18,19,31,32,44.

Modelling: Ref. Nos. 4,16,33,60,65,.

Tritium in Environmental Materials:
Ref. Nos. 7,8,9,10,11,12,14,18,20,21,36,40,45,52.

Tritium in Terrestrial Plants:
Ref. Nos. 6,7,8,10,11,12,22,24,27,28,29,30,37,46,47,49,53,59.

Tritium in Aquatic Plants:
Ref. Nos. 24,35,38,39,43,50,62.

Tritium in Terrestrial Animals:
Ref. Nos. 23,24,38,39,41,55,56,57,63,64,67,68,69,70,71.

Tritium in Aquatic Animals:
Ref. Nos. 24,34,38,39,41,43,50,54,58.

TABLE I

CONTAMINATION of ORGANIC FRACTION
on AIR OVEN DRYING

Measured tritium conc'ns in Bq/L
(combustion water or atmospheric moisture.)

Grass from CRNL Sites	Bomb Dried OBT (Bq/L)	Oven Dried OBT (Bq/L)	Atm. HTO during Drying (Bq/L)
Emergency Basin	354	507	1343
Lower Bass Lake	118	935	-
Building 360	45	131	293

R.H. Brown Unpublished data.

TABLE II

OBT AND HTO in TOMATOES and CUCUMBERS GROWN
near PICKERING NGS

TOMATOES

Harvest Date (1979)	OBT (Comb. water) (Bq/L)	Free Water T (Bq/L)	OBT/HTO
Oct 22	1528 26	477	3.20
29	1458	540	2.70
Nov 05	1839	463	3.98
12	1624	444	3.66
19	951	340	2.79
26	614	222	2.77
Dec 03	1228	255	4.81
10	762	263	2.90
17	673	259	2.60
MEAN			3.27 0.74

CUCUMBERS

MEAN of 9 SAMPLES	3.25 1.76

OBT measurements by CRNL.
Free water T measurements by Ont Hydro.

Reference: Gorman D.J. "Levels of Tritium and Carbon-14 in Greenhouse Produce at Pickering NGS." Ont Hydro Report SSD-80-2 June 1980.

TABLE III

From: Bogen D.C., G.A. Welford, C.G. White. 1979. "Tritium Distribution in Man and his Environment." Proceedings IAEA Symposium on Behaviour of Tritium in the Environment. STI/PUB/498 pp 567-574.

TRITIUM IN SOIL AND SEDIMENT

Location	Year	'Loose' tritium (pCi/ℓ)	'Bound' tritium (pCi/ℓ)	Ratio
Soil				
Chester, N.J.	1976	210 ± 40	2900 ± 100	13.8
	1977	200 ± 40	2650 ± 100	13.3
Lloyd, N.Y.	1976	190 ± 40	2800 ± 100	14.7
New York, N.Y.	1975	210 ± 40	2500 ± 100	11.9
	1976	180 ± 40	2600 ± 100	14.4
Sediment				
Sagamore Lake, N.Y.	1978	220 ± 40	3500 ± 400	15.9

TRITIUM IN FOOD

Food type	'Loose' tritium	'Bound' tritium	Ratio 'Bound'/'Loose'
Milk	250 ± 40	460 ± 50	1.8
Bread	190 ± 40	800 ± 60	4.2
Lettuce	200 ± 40	680 ± 50	3.4
Root vegetable	190 ± 40	750 ± 50	3.9
Meat	180 ± 30	520 ± 40	2.9
Fish	160 ± 30	630 ± 50	3.9

HUMAN TISSUE TRITIUM VALUES

Organ type	'Loose' tritium	'Bound' tritium	Ratio 'Bound'/'Loose'
Subject 1			
Lung	250 ± 30	530 ± 40	2.1
Liver	220 ± 30	480 ± 40	2.2
Kidney	260 ± 30	520 ± 40	2.0
Subject 2			
Lung	220 ± 30	420 ± 30	1.9
Liver	250 ± 30	400 ± 40	1.6
Kidney	190 ± 30	450 ± 40	2.4

TABLE IV

From: Strack S., L.A. Koenig. 1981. "Determination of Organically Bound Tritium in Environmental Samples by Application of the Oxidizing Plasma Technique." Kernforschungszentrum Karlsruhe Report KfK 3249.

Type of sample	Median of $R = \frac{OBT}{HTO}$
Brussels Sprouts	
Heads	2.4
Leaves	2.3
Stems	1.5
Roots	1.4
Apples	1.8
Pine Needles	1.7
Beech Leaves	2.6
Hornbeam Leaves	1.6

TABLE V

From: Koenig L.A., S.Fark, S.Hempelmann, K.G.Langguth, G.Pagliosa, D.Papadopoulos, S.Strack. 1987. "Untersuchungen zum Transport von Tritium in der Umwelt." Table 3/8 Kernforschungszentrum Karlsruhe Report KfK 4131.

TRITIUM CONCENTRATIONS in PLANT FOODSTUFFS

from the 2nd DISTRICT (EGGESTEIN-LEOPOLDSHAFEN) in the vicinity of KfK

Plant Foodstuff	Sample Date (1984)	Water Content (%)	Tritium Spec. Act. HTO (mBq/g H)	Tritium Spec. Act. OBT (mBq/g H)	OBT/HTO Ratio	Sample Date (1985)	Water Content (%)	Tritium Spec. Act. HTO (mBq/g H)	Tritium Spec. Act. OBT (mBq/g H)	OBT/HTO Ratio
Grains										
Rye	09/08	11	9±5	15±5	1.7	08/08	12	6±4	8±5	1.4
Wheat	06/08	10	10 5	14 5	1.4	08/08	15	-	7 4	-
Corn	31/10	29	18 4	22 5	1.2					
Leaf Crops										
Leaf Lettuce	20/11	85	12±5	19±6	1.6	02/12	83	9±5	12±5	1.3
Cabbages										
White	04/07	93	8±5	16±5	2.0	08/08	93	5±4	9±5	1.7
Red	04/07	92	8 5	33 6	4.1	16/09	90	6 5	-	-
Savoy	04/07	93	8 5	8 5	1.0	16/09	91	6 4	7 4	1.2
"Kohlrabi"	04/07	92	9 5	32 6	3.6	26/06	92	-	8 5	-
Brussel Sprouts	20/11	83	13 5	14 5	1.1	02/12	85	17 5	13 5	0.8
Root Crops										
Carrots	04/07	89	7±5	13±5	1.9	26/06	91	-	14±5	-
Radishes	04/07	95	6 5	18 5	3.0	08/08	95	8±5	10 5	1.3
Beets	13/09	86	7 5	9 5	1.3	08/08	86	5 4	11 5	2.2
Potatoes	13/09	77	9 5	17 5	1.9	16/09	76	10 5	11 5	1.1
Asparagas	29/05	90	7±5	28±6	4.0	11/06	91	9±5	12±5	1.3
Fruit										
Strawberries	04/07	91	6±5	22±6	3.7	26/06	89	7±4	6±5	0.9
Apples	13/09	84	8 5	8 5	1.0	16/09	83	10 5	11 5	1.1
Mean Values			8±5	17±5	2.16			6.0±4.4	11±5	1.33

TABLE VI

From: Hisamatsu S.,Y. Takizawa, T. Abe, T. Katsumata 1986. "Determination of Fallout Tritium in Food." Report of the Energy Project (Nuclear Fusion) of Ministry of Education and Culture of Japan. No. 60050024.

R1 Duplicate analyses of tritium in tissue binding water(Bq/l).

Sample	1st	2nd
Meats	3.3+-0.3	3.4+-0.3
Beans	4.3+-0.3	4.1+-0.3

R2 Variation of tritium concentration in tissue binding water(Bq/l).

Sample	1984	1985
Meats	3.2+-0.3	3.3+-0.3
Eggs	3.3+-0.3	3.3+-0.2

R3 Tritium concentration in food collected at Akita during 1985

Sample	Free water Bq/l	Free water mBq/d	Tissue binding Water Bq/l	Tissue binding Water mBq/d	TB/FW(Bq/l)
Rice	4.4+-0.3	100+-6	3.2+-0.3	350+-30	0.73+-0.07
Cereals without rice	2.5+-0.3	90+-9	3.6+-0.3	130+-10	1.4+-0.2
Potatos	2.4+-0.3	110+-13	2.7+-0.3	24+-3	1.1+-0.2
Sugar	-	-	1.0+-0.3	6.7+-1.6	-
Confectionary	2.6+-0.3	3.9+-0.4	1.6+-0.2	22+-3	0.60+0.10
Beans	2.3+-0.2	93+-10	4.3+-0.3	54+-4	1.9+-0.2
Soyasauces	1.3+-0.3	24+-5	5.3+-0.2	16+-1	4.0+-0.8
Fruits	1.9+-0.3	250+-40	2.6+-0.3	39+-4	1.4+-0.3
Green vegetables	2.4+-0.3	110+-10	2.6+-0.3	4.9+-0.5	1.1+-0.2
Oter vegitables	1.2+-0.2	230+-40	3.0+-0.3	26+- 2	2.4+-0.5
Algae	-	-	1.2+-0.2	2.4+-0.3	-
Fish/Shellfish	(0.47+-0.24)	(32+-16)	1.9+-0.2	29+-3	(4.1+-2.1)
Meats	2.7+-0.2	120+-10	3.3+-0.3	46+-4	1.2+-0.2
Eggs	2.7+-0.3	75+-7	3.3+-0.2	19+-1	1.3+-0.1
Milks	2.7+-0.3	270+-30	3.0+-0.4	26+-3	1.1+-0.2
Oils	-	-	3.7+-0.2	45+-3	-
Total	2.0+-0.1	1500+-70	3.1+-0.1	840+-30	1.6+-0.1

R4 Tritium concentration in tap water at Akita.

Date	Bq/l
1984	
May	1.8+-0.3
Jun	3.0+-0.3
Aug	3.1+-0.3
1985	
Feb	3.2+-0.3
Mar	1.6+-0.2
May	1.5+-0.2
Jun	2.8+-0.3
Jul	2.7+-0.3
Aug	2.8+-0.3
Sep	2.8+-0.2
Oct	3.0+-0.3

R5 Total Ingestion Intake of Fallout Tritium.

	Present Study Water l/d	^3H Bq/l	Bq/d	%	Bogen[a] ^3H Bq/d	Clemente[b] Bq/d
Oxidation of Diet	0.27	3.1	0.84	14	7.0	36
Free Water in Diet	0.77	2.0	1.5	24	9.9	} 15
Other Water	1.46	2.6[c]	3.8	62		
Total	2.50[d]		6.1	100		51

a):1978, New York, Bogen, D.C. et.al, IAEA-SM-232/75.
b):1975-1978, Italy, Clemente, G.F. et.al, IAEA-SM-237/64.
c):mean of monthly concentration in tap water during 1985, lacks of data were completed by linear completion.
d):(ratio of water intake to body weight for Reference man)x(mean of body weight of reference Japanese man for both sexes).

TABLE VII

From: Tritium and plutonium content in the food-chain in Italy.
G.Ingrao, P.Belloni, G.F.Clemente, S.Di Pietro, G.Santori
Symposium on the Transfer of radioactive materials in the terrestrial environment subsequent to an accidental release to the atmosphere.
Vol.II, page 481-495, Dublin, 11 April 1983.

MEAN TRITIUM CONCENTRATION ± S.E. IN SINGLE FOOD ITEMS AND TOTAL DIETS COLLECTED IN VARIOUS ITALIAN REGIONS.

	BOUND	HTO	OBT/HTO
	mBq/g dry weight	mBq/ml	
MACARONI	75.8 ± 10.4	9.6 ± 2.6	14. +/- 4
MEAT	259.0 ± 96.2	15.9 ± 5.1	26. ± 13
FISH	≤55.5	23.7 ± 8.9	< 3.7
CHEESE	≤55.5	45.9 ± 5.2	< 1.4
FRESH MILK	86.2 ± 11.8	29.2 ± 7.4	3.6 ± 1
PROCESSED MILK	86.6 ± 16.3	9.3 ± 2.2	11.5 ± 4
ROOT VEGETABLE	≤55.5	14.4 ± 8.9	< 6.9
LEAFY "	≤55.5	22.2 ± 5.2	< 4.5
FRUITY "	65.9 ± 17.8	9.6 ± 2.2	12.3 ± 4
FRUIT	99.2 ± 25.5	27.7 ± 13.7	6.4 ± 4
EGG	≤55.5	12.2 ± 5.5	< 5.6
WINE	---	19.6 ± 1.8	-
DRINKABLE	---	9.6 ± 1.5	-
TOTAL DIET	191.3 ± 70.3	50.3 ± 22.2	6.0 3.5

TABLE VIII

From: Belloni P., G.F. Clemente, S. Di Pietro, G. Ingrao. 1983. "Tritium Levels in Blood and Urine Samples of the Members of the Italian General Population and Some Exposed Subjects." Radiation Protection Dosimetry, Vol. 4, No. 2 pp 109-113.

TRITIUM LEVELS IN BLOOD AND URINE SAMPLES

Tritium concentrations in urine and blood samples of members of the general population living in various Italian regions.

Group A (Castrovillari — CS)

Subject no.	Age	Sex	Body weight kg	Body height cm	Tritium concentration ± 2 σ		Ratio Blood/Urine
					Total blood pCi.ml^{-1}	Urine pCi.ml^{-1}	
1	37	F	95	172	6.7 ± 1.9	1.4 ± 0.5	4.78
2	20	M	52	158	5.0 ± 1.8	0.7 ± 0.5	7.14
3	38	M	73	165	13.4 ± 2.1	1.8 ± 0.5	7.24
4	37	F	50	160	5.8 ± 1.9	0.7 ± 0.5	8.28
5	40	F	82	173	12.7 ± 1.9	1.9 ± 0.5	6.68
6	38	M	68	162	—	≤ 0.5	—
7	38	F	60	157	6.1 ± 1.8	0.9 ± 0.5	6.78
Average ± S.E.					8.28 ± 1.53	1.23 ± 0.22	6.82 ± 0.47

Group B (Novazza – BG)

Subject no.	Age	Sex	Body weight kg	Body height cm	Tritium concentration ± 2 σ		Ratio Blood/Urine
					Total blood pCi.ml^{-1}	Urine pCi.ml^{-1}	
8	43	F	50	175	4.1 ± 1.5	0.6 ± 0.2	7.42
9	29	F	58	170	4.0 ± 1.5	0.5 ± 0.2	7.69
10	24	F	90	180	5.4 ± 1.6	1.0 ± 0.2	5.31
11	38	F	53	155	4.3 ± 1.6	0.9 ± 0.2	4.89
12	37	F	70	170	4.0 ± 1.5	0.5 ± 0.2	7.44
13	44	F	70	163	7.2 ± 1.6	0.7 ± 0.2	10.30
14	26	M	75	170	7.5 ± 1.6	0.8 ± 0.2	9.98
15	21	M	70	170	5.1 ± 1.6	0.6 ± 0.2	9.05
16	47	M	73	180	6.5 ± 1.6	0.8 ± 0.2	8.15
17	25	M	63	167	10.4 ± 1.6	1.7 ± 0.2	6.07
18	36	M	75	168	2.7 ± 1.5	0.5 ± 0.2	4.98
Average ± S.E.					5.56 ± 0.66	0.78 ± 0.11	7.39 ± 0.58

Tritium concentration in urine and blood samples of some occupational exposed workers

Subject no.	Age	Sex	Body weight kg	Body height cm	Tritium concentration ± 2σ		Sampling date month/year	Ratio Blood/Urine
					Total blood pCi.ml^{-1}	Urine (HTO) pCi.ml^{-1}		
1	56	M	83	169	200 ± 3	2200 ± 9	VI 1978	0.09
						122 ± 2	X	
2	56	M	50	154	141 ± 3	196 ± 3	VI 1978	0.72
						194 ± 3	X	
3	43	M	68	156	217 ± 3	244 ± 3	VI 1978	0.89
						211 ± 3	X	
4	41	F	90	164	188 ± 3	120 ± 2	VI 1978	1.57
						52 ± 2	X	

TABLE IX

From: Rodgers D.W., 1988. "Tritium Dynamics in Mice Exposed to Tritiated Water, Tritiated Diet or Both." Ontario Hydro Research Division Report 88-30-K.

Estimated Steady State Activity and Rate Constants of Tissue Water Tritium of Mice Exposed to Tritiated Water, Diet or Both (Estimate ± SE)

Tritium Source	Steady State Activity Q(eq) (kBq/g H)	Rate Constant During Exposure k_1 (/d)	Following Exposure k_2 (/d)
Water (22.9 kBq/g H)	15.9 ± 0.1	0.68 ± 0.03	0.46 ± 0.02
Diet (34.4 kBq/g H)	7.0 ± 0.1	0.34 ± 0.03	0.27 ± 0.02
Both	22.8 ± 0.1	0.55 ± 0.02	0.41 ± 0.01

Estimated Steady State Activity and Rate Constants of Organically Bound Tritium of Mice Exposed to Tritiated Water, Diet or Both (Estimate ± SE)

Tritium Source	Compartment Activity			Rate Constant		
	During Exposure		Following Exposure	During Exposure		Following Exposure
	Q(eq)	$Q_{(s)}$	$Q_{(s)}$	k_1	k_3	k_3
	(kBq/g H)			(/d)		
Water (22.9 kBq/g H)	3.5 ±0.1	1.6 ±0.5	2.7 ±0.6	0.16 ±0.01	0.31 ±0.23	0.029 ±0.001
Diet (34.4 kBq/g H)	42.6 ±0.8	20.3 ±8.5	27.8 ±9.6	0.11 ±0.01	0.21 ±0.15	0.026 ±0.013
Both	46.1 ±0.8	26.1 ±4.0	29.7 ±4.2	0.11 ±0.01	0.36 ±0.14	0.023 ±0.006

TABLE X

From: Moghissi A.A., E.W. Bretthauer, R.G. Patzer. 1987. "Biological Concentration of ^{3}H." Health Physics Vol. 53 No. 4 pp 385-388.

Average ratio of organic to aqueous ^{3}H (OT/OA) in various organs of rabbits

Tissue	P	F_w	F_s	F_3	Average
Liver	1.17 ± 0.20	1.05 ± 0.12	0.933 ± 0.202	0.938 ± 0.093	1.02 ± 0.08
Kidney	1.08 ± 0.11	1.06 ± 0.15	0.926 ± 0.043	0.960 ± 0.113	1.01 ± 0.06
Lung	0.994 ± 0.130	0.950 ± 0.246	0.990 ± 0.086	0.945 ± 0.083	0.97 ± 0.08
Brain	0.885 ± 0.052	0.901 ± 0.110	0.711 ± 0.057	0.904 ± 0.023	0.85 ± 0.05
Muscle	0.969 ± 0.097	1.08 ± 0.19	1.04 ± 0.08	1.13 ± 0.08	1.05 ± 0.06
Skin	0.963 ± 0.189	0.967 ± 0.123	1.08 ± 0.10	1.00 ± 0.12	1.00 ± 0.07
Average	1.01 ± 0.07	1.00 ± 0.08	0.95 ± 0.05	0.98 ± 0.04	0.98 ± 0.03

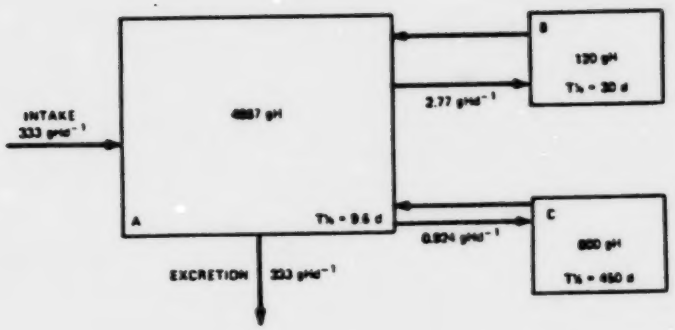


Figure 1: National Council of Radiation Protection and Measurements three-compartment model of hydrogen in the body. Reference (2).

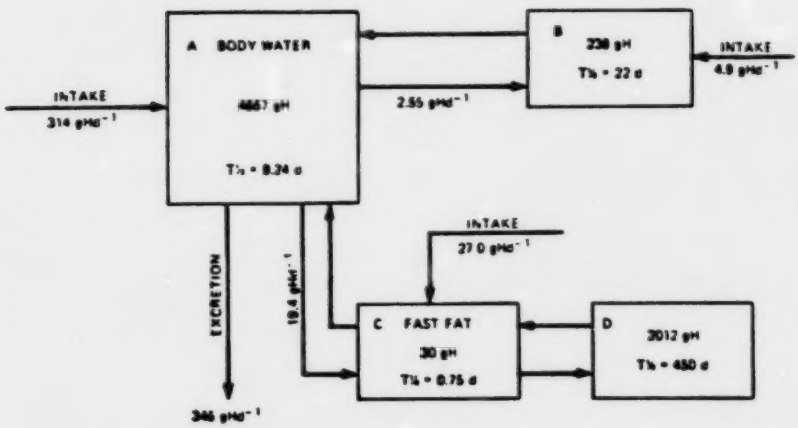


Figure 2: Four-compartment model of hydrogen metabolism of Etnier, Travis and Hetrick. Reference (4).

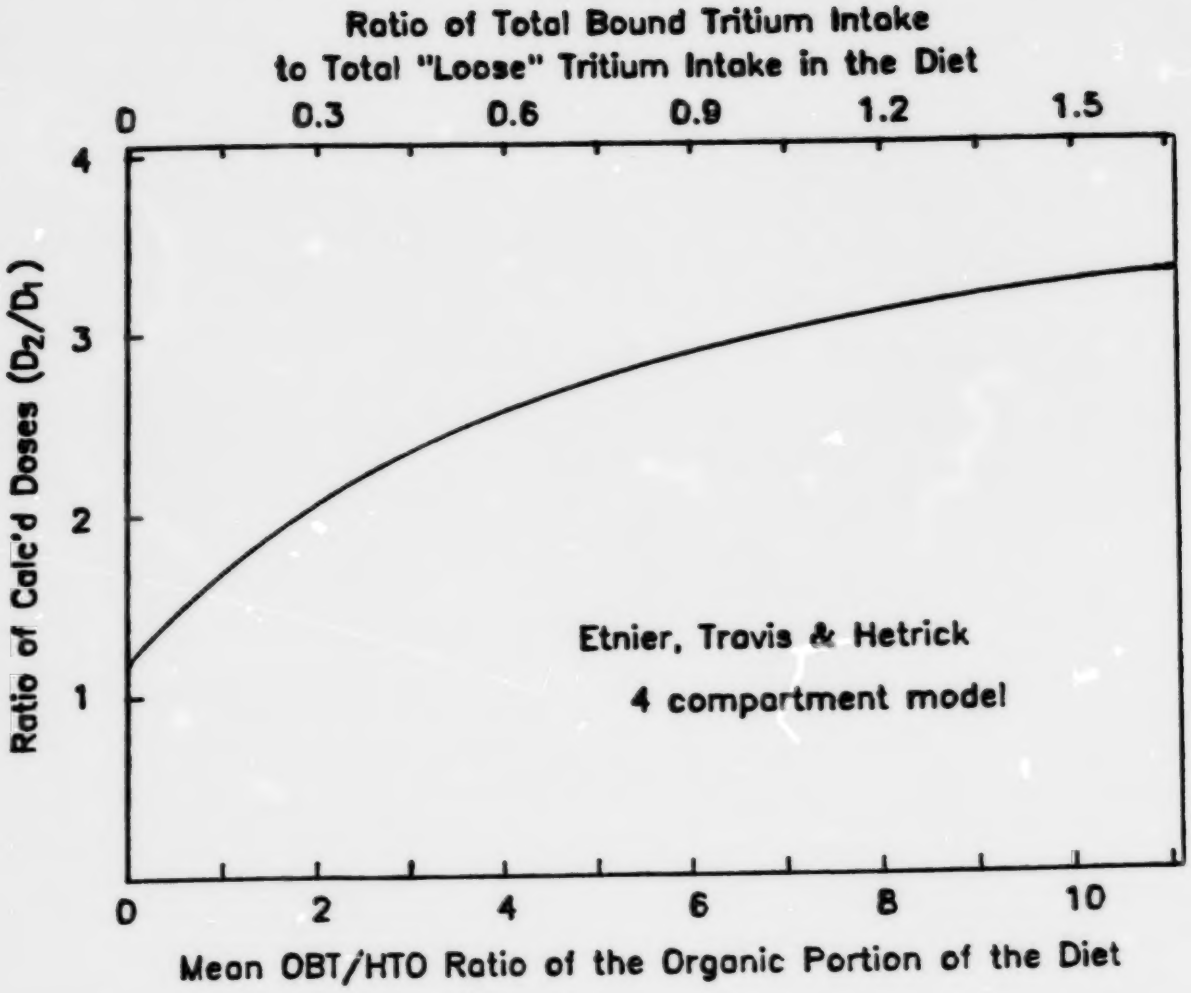


Figure 3: Etnier,Travis & Hetrick metabolism model prediction of the ratio of cumulative total body dose, D_2 , to free body water dose, D_1 , after 2000 days as a function of the ratio of OBT to HTO in the diet. Adapted from Fig.4 in Reference 3.

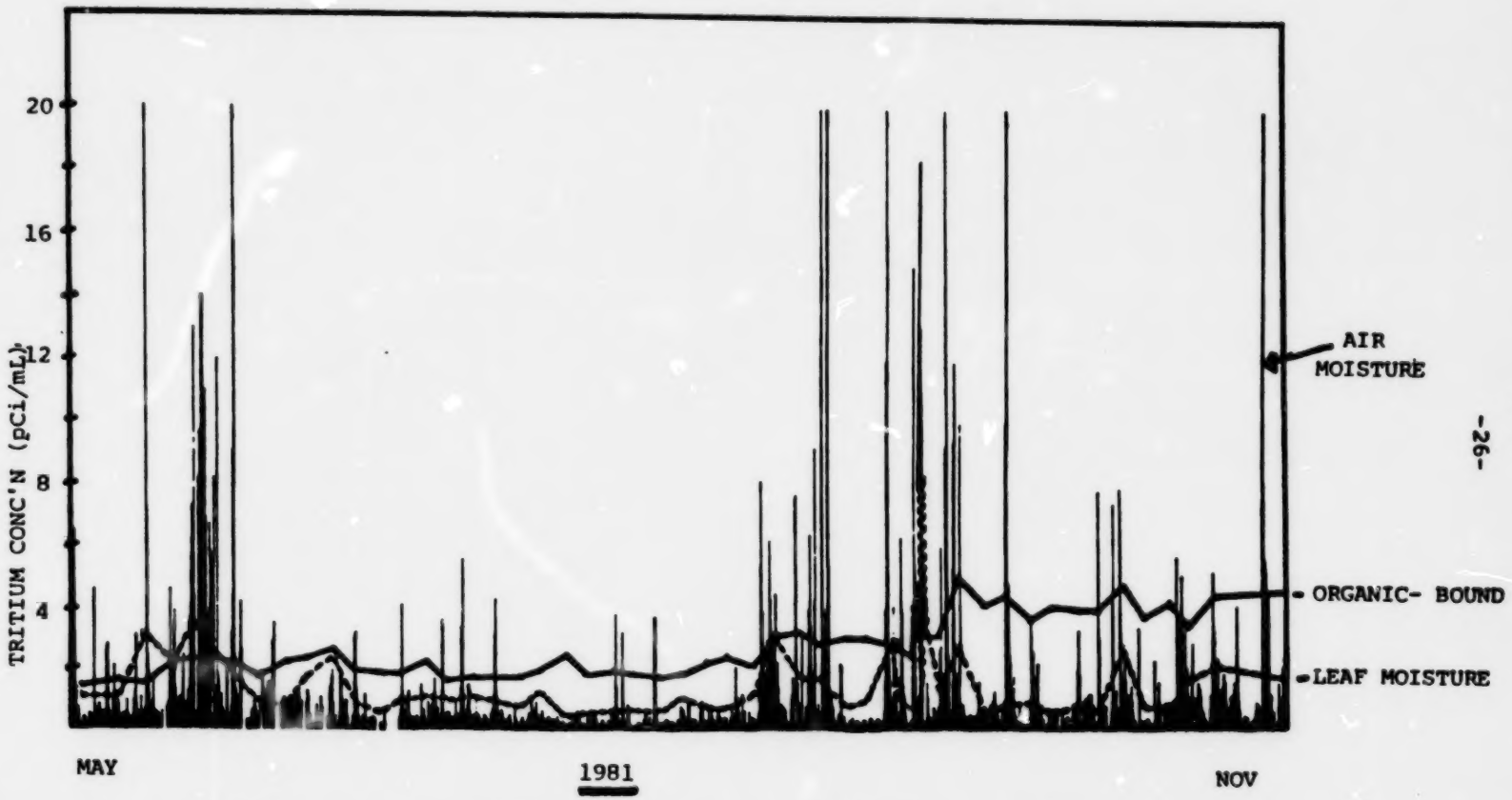
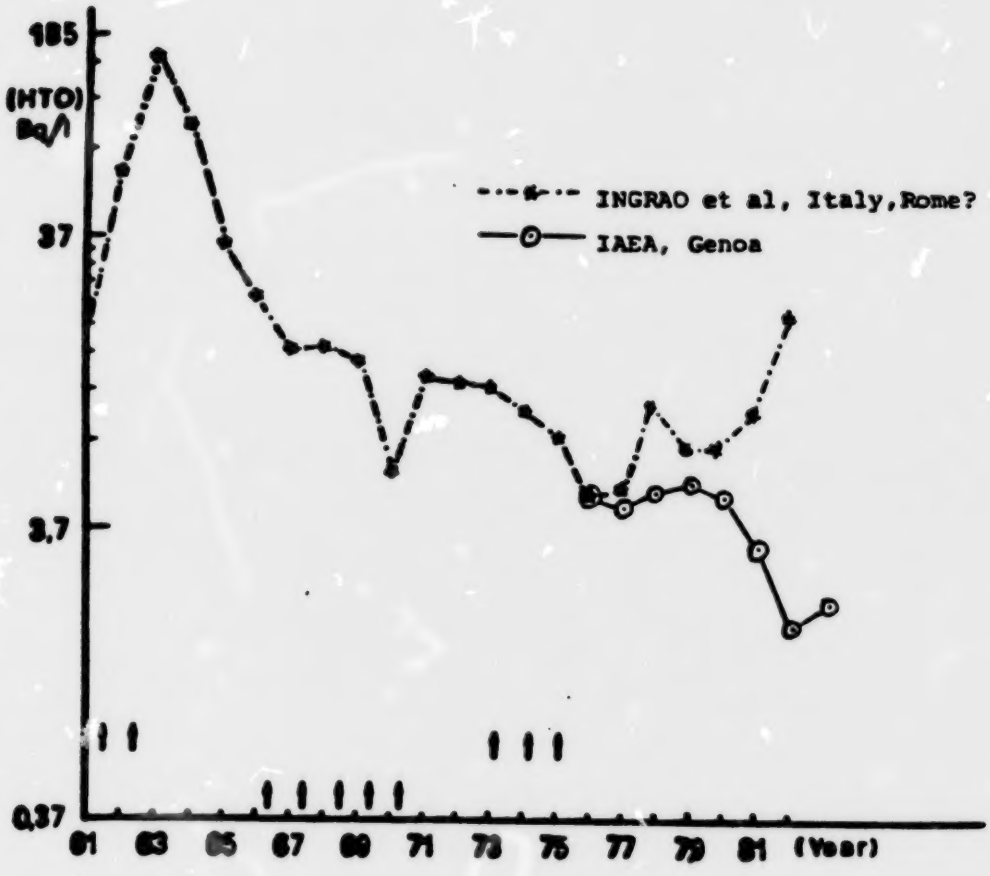


Figure 4: Tritium in Beech Leaves and Air Moisture at Karlsruhe, West Germany.
S. Strack, Annales de l'Assoc. Belge de Radioprotection. Vol. 7 No. 3,4 (1982).



TRITIUM IN PRECIPITATION IN ITALY

Figure 5:

From: Tritium and plutonium content in the food-chain in Italy.
G.Ingrao, P.Belloni,G.F.Clemente,S.Di Pietro, G.Santori
Symposium on the Transfer of radioactive materials in the terrestrial environment subsequent to an accidental release to the atmosphere.
Vol.II, page 481-495, Dublin, 11 April 1983.

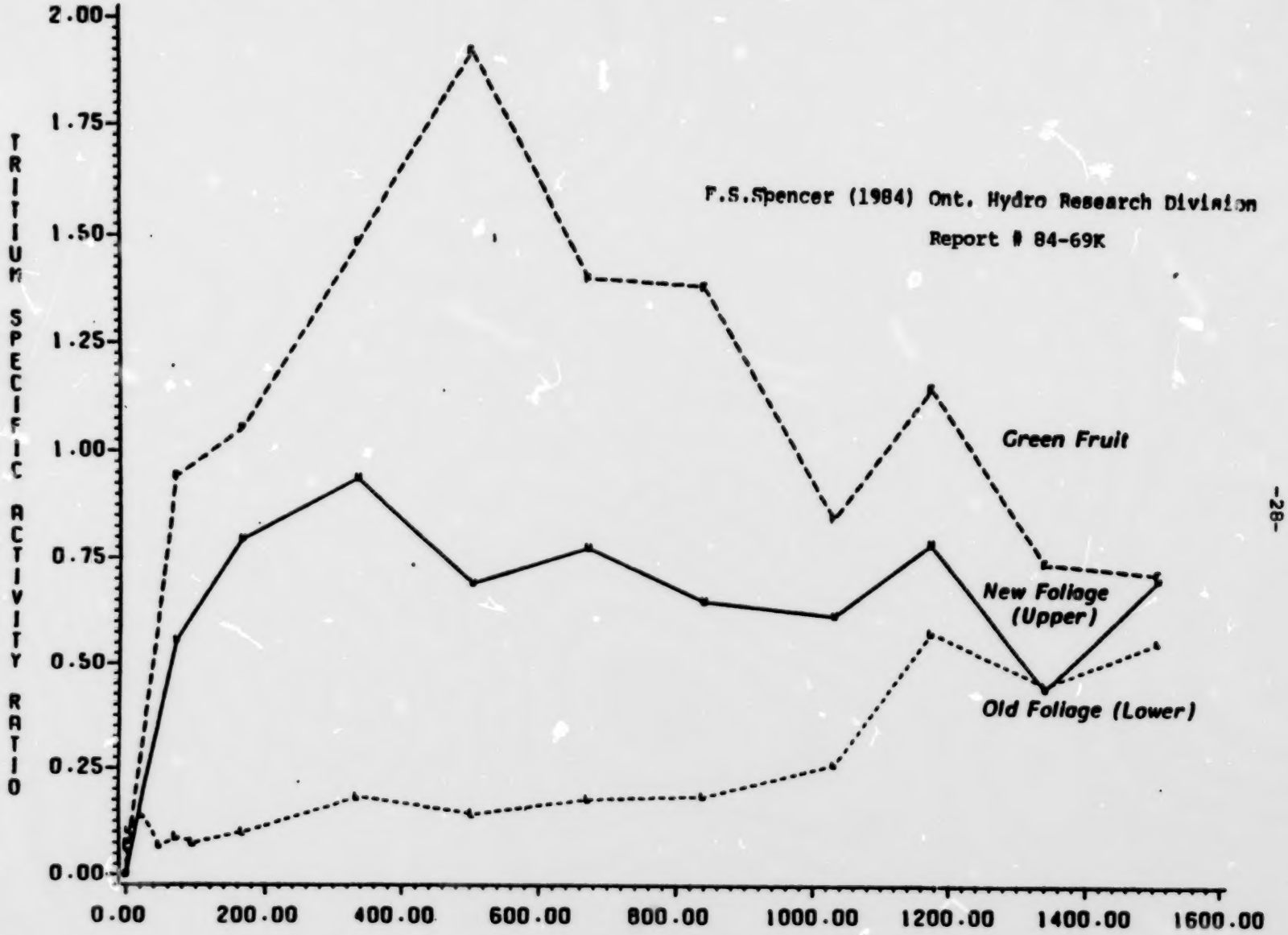


FIGURE 6
CHANGES IN TRITIUM SPECIFIC ACTIVITY RATIO OF OBT TOTFWT DURING HTO UPTAKE

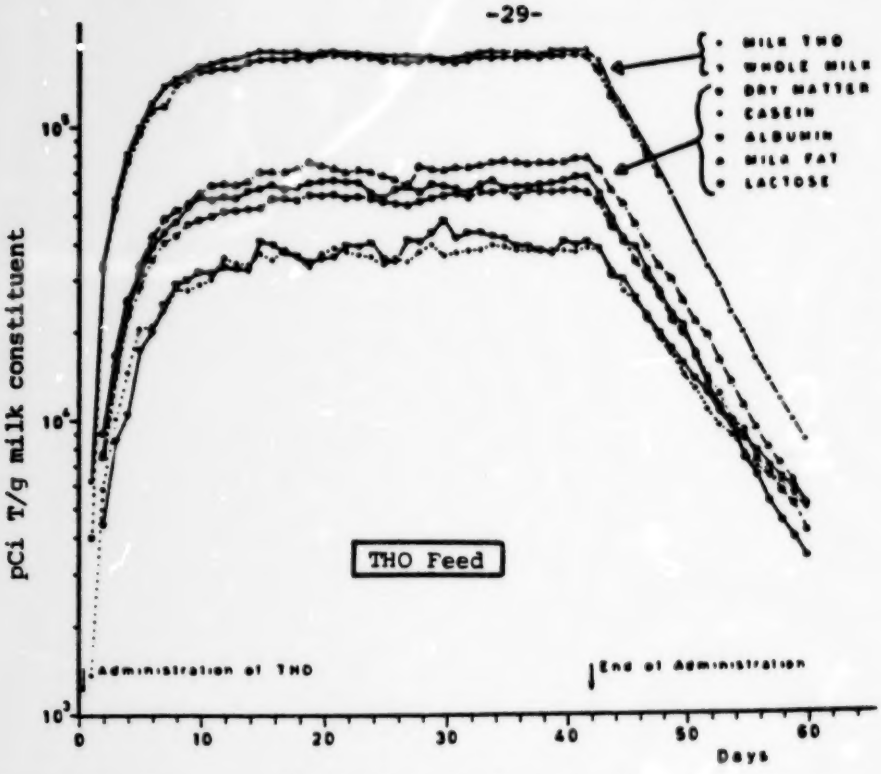


Figure 7a: *The evolution of ^3H activity in milk and in milk constituents after continuous administration of THO for 41 days to a lactating cow.*
From: Potter G.D., Vattuone G.M., McIntyre D.R. Health Physics 22 (1971) 405.

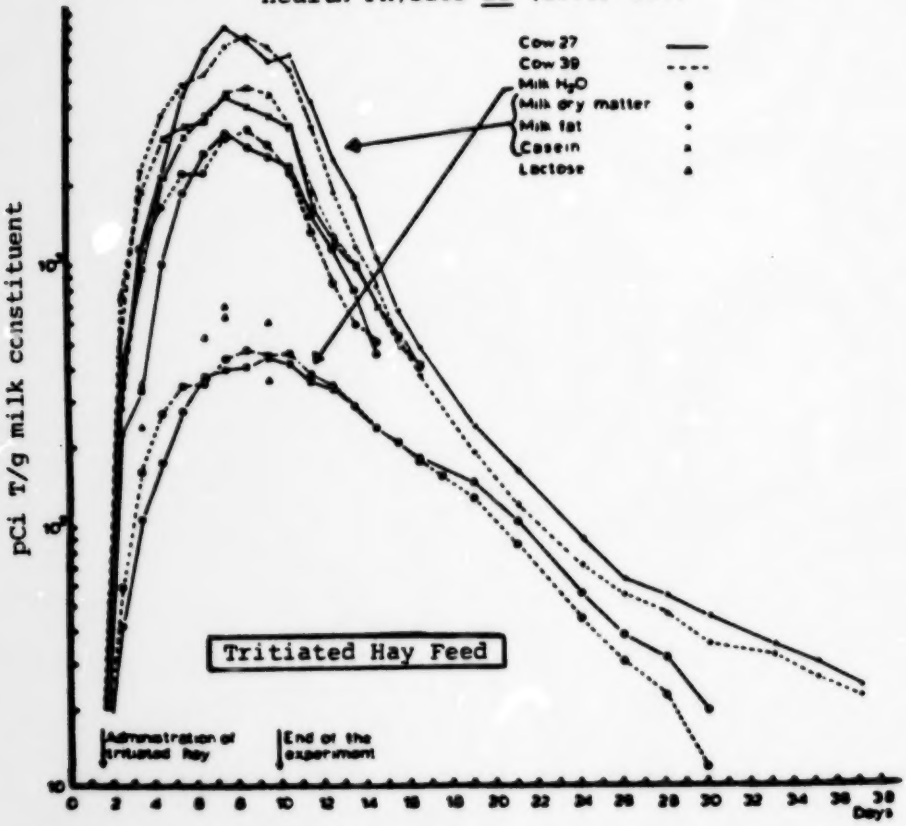


Figure 7b: *Tritium activity in various milk fractions (milk H_2O, total dry matter, milk fat, casein and lactose) after administration of organically bound tritium (tritiated hay) to two lactating cows.* From: Fig.5 of IAEA Tech. Report No. 207 (1981).